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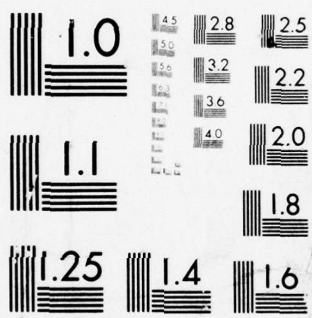

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TECHNICAL REPORT ARLCB-TR-77031

EROSION IN 81MM MORTAR TUBES

V. Peter Greco

July 1977

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER WEAPON SYSTEM LABORATORY
BENÉT WEAPONS LABORATORY
WATERVLIET, N. Y. 12189

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A laboratory erosion tester has been designed and developed for predicting the service performance of protective coating materials in the bores of mortar systems using rounds with tail fins. Due to the use of newly designed ammunition, the service life of 81MM mortar tubes has been reduced to approximately one third of its original life as the result of the formation of three rings on annular groove erosion formed in the bore. Preliminary efforts to apply wear resistant bore coatings and test fire them in the field have been extremely costly and

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time consuming because of the large number of rounds required (approximately 7500).

The laboratory erosion tester has been designed to ignite the actual tail fin assembly (which causes the erosion) in a chamber which holds eight test specimens to be evaluated at the same time. The erosion rate of the test material can be increased so that less rounds are required, by merely reducing the distance of the jet stream and moving the specimens closer to the tail fin assembly which upon ignition, radially discharges the mixture of hot gases and associated burning particles onto the specimen surface.

This progress report presents the erosive behavior of eight candidate coatings which have been tested in the laboratory erosion tester. Laboratory results have shown that a five mil thick cobalt or cobalt alloy deposit should be suitable to resist erosion and increase the service life of the 81MM mortar system. An overlay of 2/10 of a mil of chromium over cobalt further increases the erosion resistance. Further testing is necessary to specifically determine the best cobalt system and chromium conbination. The next effort would be to field test the coating in the actual mortar system to verify the laboratory results.

ACKNOWLEDGEMENT

Credit is extended to Dr. J. A. Walden for monitoring the firing tests and obtaining the wear data. The author also wishes to thank Messrs. W. Baldauf, P. Giordano, R. Messier, and W. Coughlin for their assistance in obtaining the firing data.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont)

LIST OF TABLES

HISTORICAL BACKGROUND

A. Annular Groove Erosion in 81MM Mortar Tubes

Erosion of cylinder bores is typically encountered in gun systems and recoilless rifles. Erosion of bores in Mortar systems would not normally be expected in view of the relatively low chamber pressures and low projectile velocities associated with the weapon. However, due to changes in the design of the tail fin assembly in the 81MM M29A1 Mortar System, excessive damage to the tube bore surface has been found during its early firing life which has rendered the tube unserviceable after approximately 7000 rds as compared to the normal service life of 20,000 rds before condemnation.*

B. Nature and General Cause of Erosion

The surface damage due to erosion occurs in the form of 3 annular grooves presumably due to the jet impingement of hot gases and cartridge material flowing from the vent holes of the tail fin assembly of the mortar round. The major changes in the system which are suspected in creating the erosion problem are:

a. A quantity of 20 vent holes having a .196" diameter were replaced with 24 holes having a .125" diameter which obviously increased the velocity of the eroding gaseous atmosphere at the point of contact on the bore surface.

b. The use of an ignitor cartridge without a copper sleeve in the center as shown in Figure 1.

Figure 1A shows a mortar tube with a section cut to reveal the three annular grooves of erosion. Figure 2 shows an illustration of the eight rows of three jets of igniting gases impinging on the bore surface as one looks through the bore. Figure 3 attempts to illustrate the flow pattern of the eroding gaseous atmosphere emanating from the 24 holes of the tail fin assembly (apart from its projectile) onto a sectional view of the bore surface.

*As a result of the annular groove erosion, a maximum wear limit of .022" on the diameter of the bore has been established before condemnation of the mortar tube.

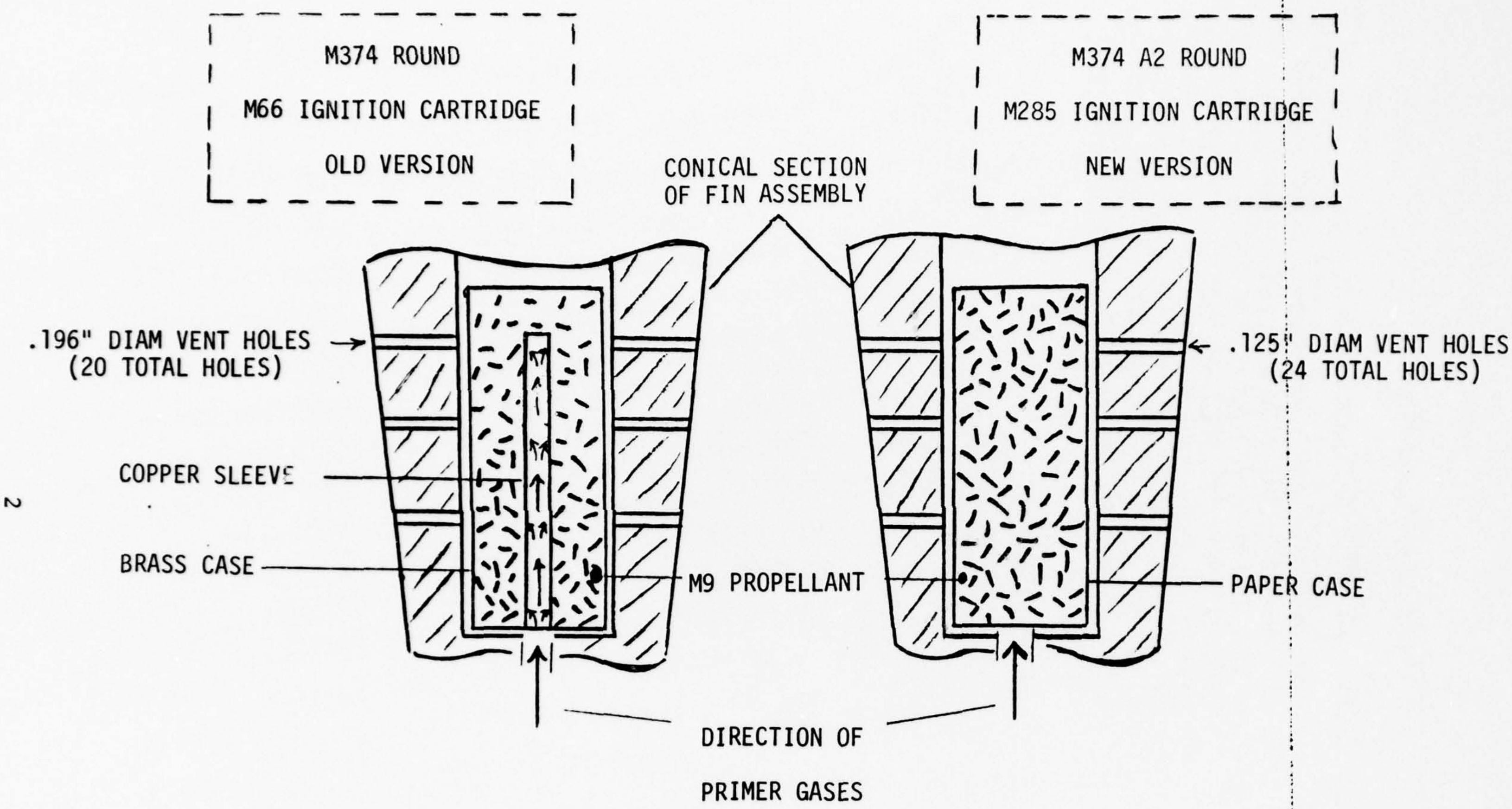


Figure 1. Comparison of old and new version of ignition cartridge.

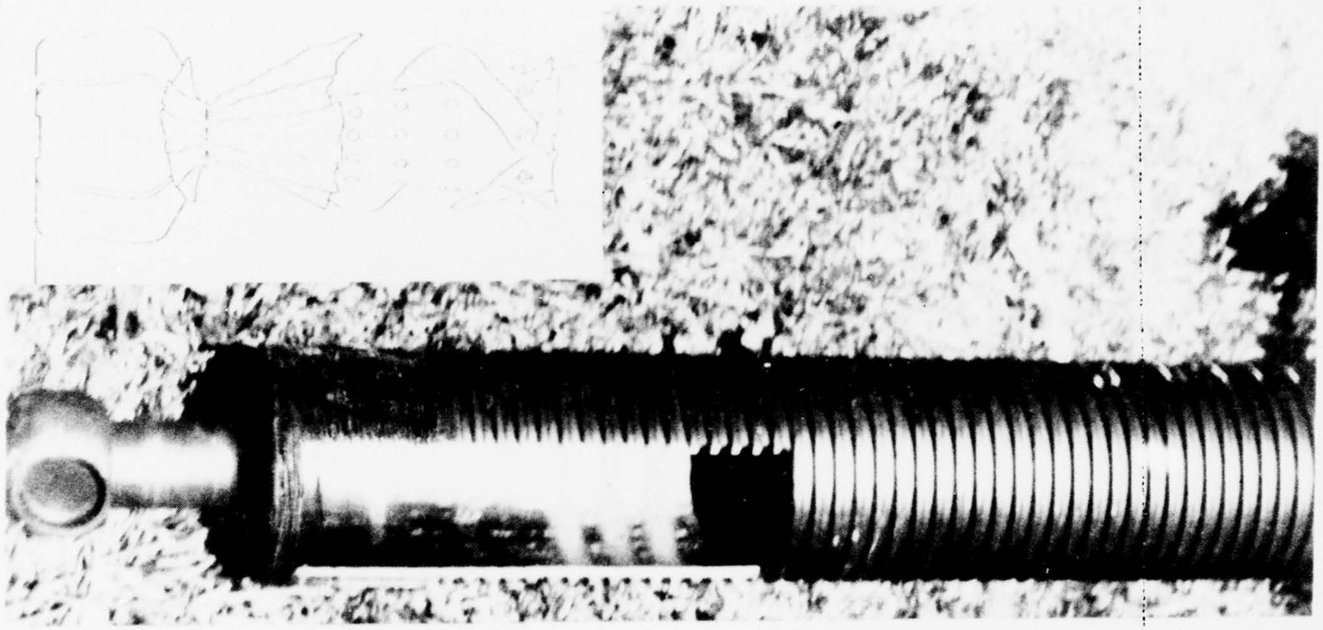


Figure 1A. 81mm mortar tube cut out to reveal the three eroded annular grooves (Inset is sketch of tail fin showing propellant bags (for higher increment charges) that deflect gases which otherwise impinge on the bore surface.)

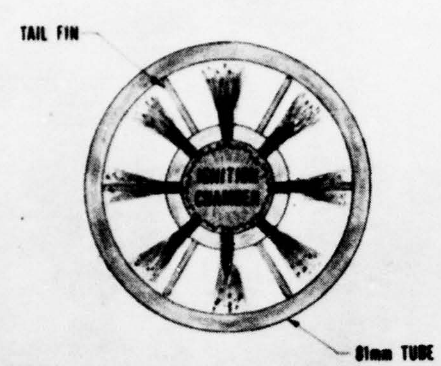


Figure 2. Overhead view of the eight jets of igniting gases impinging on the bore surface.

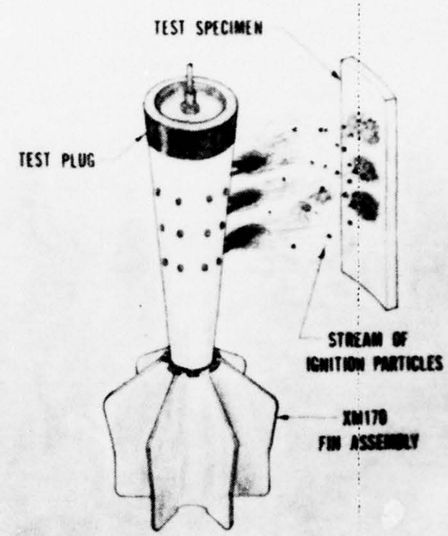


Figure 3. Sectional view of igniting gas jets impinging on test specimens.

From a single round of firing a very slight degree of damage is caused by the jet of hot gases and propellant particles streaming from each of the 1/8" holes of the tail fin assembly. The bore damage caused from a single jet of hot gas only covers a circular area of approximately 1/2 inch diameter. However, with the firing of several thousand of rounds which are loaded in the mortar tube in a random position (circumferentially) the resulting accumulated surface damage is formed in a pattern of 3 circumferential annular grooves spaced opposite to the 3 rows of holes on the tail fin assembly.

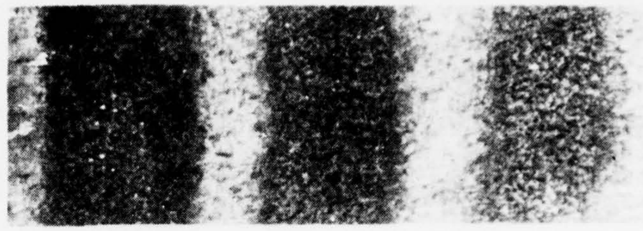
The 81MM Mortar System is designed to fire rounds using various increments of propellant (i.e. from 0 to 9). Increments from 1-9 require a corresponding number of propellant bags which are physically placed around the tail fin assembly (inset in Figure 1). The chamber pressures increase with increasing increment (i.e. 900 psi with increment 0 and 8400 psi with increment 9). Along with burning time and flame temperature, the amount of bore erosion in rifled gun systems is also increased with increasing chamber pressures. Suprisingly, however, in the case of the 81MM Mortar System damage to the bore surface is most severe when a "0" increment round is fired (i.e. low pressure) because no bags are placed around the tail fin assembly to obstruct the jet stream of gases from directly impinging on the bore surface. The low pressure referred to, of course, is misleading since it is the peak chamber pressure. The pressure value of importance is that which is pinpointed on the bore surface from the gas jets.

C. Erosion Characteristics in the 81MM M29A1 Mortar System

A severely eroded 81MM Mortar Tube (which was fired in the field) was metallographically studied in an attempt to determine the significant factors leading to the annular groove erosion which form the 3 rings. Figure 4a shows a sectional surface view of the 3 annular grooves. Figure 4b shows the longitudinal cross-sectional profile of the forward eroded groove. While visual examination of the eroded surface shows a severe pitted condition which appears to be caused by purely mechanical forces, microscopic cross-sectional examination (see Figures 4c and 4d) has revealed patches of the typical white layer (presumably due to thermal cycling) normally found in large caliber rifled gun tubes.

(A)

SURFACE VIEW OF THE
3 ERODED ANNULAR GROOVES
(DARK BANDS)



(B)

LONGITUDINAL CROSS SECTION
SHOWING PROFILE OF THE
FORWARD ERODED GROOVE

(C)

MICROSCOPIC SURFACE VIEW
OF FORWARD GROOVE SHOWING
WHITE LAYER ON PEAKS

(D)

MICROSCOPIC SURFACE VIEW
OF THE FORWARD GROOVE
SHOWING SEVERAL CRACKS

Figure 4. Eroded views of a condemned 81mm mortar tube after field firing of approximately 7500 rounds.

OBJECTIVE

The primary purpose of this investigation was to search for a surface coating which could be economically applied to the mortar bore to resist erosion and increase the service life up to its original performance. In order to achieve such an objective, a number of coatings had to be tested and evaluated.

THEORETICAL CONSIDERATIONS IN THE FORMATION OF PITTING EROSION

Unfortunately, a mechanism for such erosion was not easily obtainable, since we were dealing with a jet stream of hot gases and associated propellant particles with various degrees of burning and trajectories at point of impact. Furthermore, an exact analytical solution appeared impossible, even if treated as a simple mechanism of erosion.

However, since it appeared that the particular pitted surface damage encountered in the 81MM Mortar System was primarily formed by abrasive or cutting forces, it was considered appropriate to review the open literature as a guide in approaching a solution to the problem. A review of the literature on gun bore erosion offered no help, even though the grooved erosion was somewhat similar to the erosion sometimes formed at the end of cartridge cases. By the same token, none of the investigations reported in the open literature could be matched with the combined factors existing in the Mortar System, but it was hoped that some of the erosion studies could be of some help to us. As one might expect, the studies reported in the literature on impact erosion varied considerably.

For example, some investigators have studied the impingement of abrasive particles on a metal surface, some looked at the effects of steel or glass spheres striking a surface and some studied the collapse of water droplets which causes cavitation erosion. Still others have looked at striking abrasive particles in a fluid stream, while some have studied the effects of hot turbine gases on a metal surface. Some of these study areas revealed some similarities in the behavior and damage characteristics of metal surfaces and warrant some discussion.

Finnie[1-5] et al appeared to be the first to analytically study the manner in which abrasive particles erode the surface of a ductile metal and was quick to point out that a general disadvantage of erosion data in the literature is that particle velocities as distinct from fluid velicities, had not previously been measured. He points out also that ductile surfaces should be given separate attention from brittle surfaces since their erosion behavior is significantly different.

In solving the equations of motion of a single abrasive particle striking a ductile surface[3], it was shown that the volume Q removed by a given mass of abrasive grains with velocity V and angle α is estimated to be

$$Q = C \frac{MV^2}{4} \frac{1}{p} f(\alpha)$$

where p is the flow stress (relative to the surface). In Figure 5, the dashed line shows $f(\alpha)$, the predicted variation of erosion with angle for a ductile material eroded by abrasive particles. The scale of $f(\alpha)$ was chosen arbitrarily so that its maximum value agrees with the experimental data for aluminum. Finnie et al[3] reported good correlation of wear with experiments showing the greatest wear to be at angles 17°-20° (see Figure 5). However, the equation does not hold very well for angles nearer 90° which is what we are dealing with in our present case. The three possible effects which invalidate the simple theory for ductile surfaces at angle 90° is:

a) Not all particles will strike the surface at the same angle.

b) The analysis considers a smooth surface and after the surface is roughened the particle-surface interaction is changed.

c) The surface becomes cold worked and embrittled and no longer behaves in a predictable manner.

---

1. Finnie, I., "The Mechanism of Erosion of Ductile Metals," Proceedings of the 3rd National Congress of Applied Mechanics, American Society of Mechanical Engineers, 1958, pp. 527-532.

2. Finnie, I., "Erosion of Surfaces by Solid Particles," Wear, Vol. 3, 1960, pp. 87-103.

3. Finnie, Iain, Wolak, Jan, and Kabil, Yehia, "Erosion of Metals by Solid Particles," Journal of Materials, Vol. 2, No. 3. Sept. 1967, pp. 682-700.

4. Sheldon, G.L., Finnie, I., "On the Ductile Behavior of Nominally Brittle Materials During Erosive Cutting" Journal of Engineering for Industry, Nov. 1966, pp. 387-392.

5. Sheldon, G.L. and Finnie, I., "The Mechanism of Material Removal in the Erosive Cutting of Brittle Materials," Transactions, American Society of Mechanical Engineers, Vol. 88B, 1966, pp. 387-392.

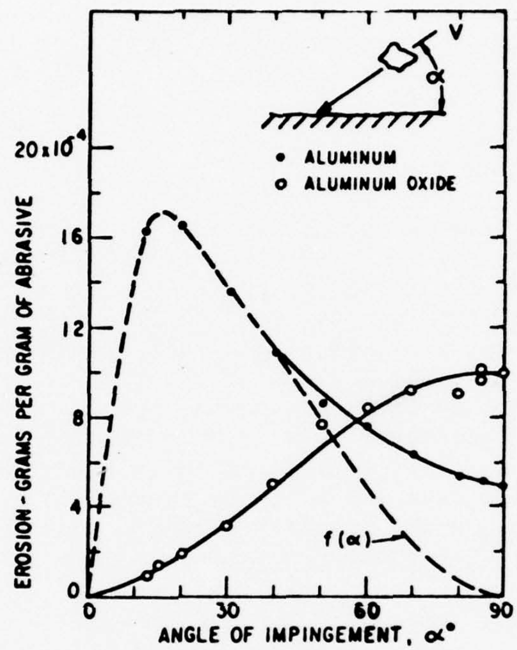


Figure 5. Weight removed by erosion as function of angle of impingement for 1100-0 aluminum and high density aluminum oxide (after Finnie ref 3).

One point of interest in the case of brittle surfaces (Figure 5), is that 90° angle of impingement produces the greater amount of wear. It will be shown later that some of our own results have shown similar behavior.

Engel[6-7] reported that the development of a pit-depth vs velocity equation for collision of rigid spheres on a surface does not hold in every case where cold working of the surface occurs. This has also been pointed out by Moore, et al[8] in their studies of worn metal surfaces using a blunted tool.

As previously mentioned, the above studies cited from the literature involve process conditions which are quite remote from the environmental factors which exist in the Mortar System. To begin with the particles are neither jagged abrasives, metal spheres or water droplets but propellant platelets or discs which are at an indeterminate rate of burning at the point of contact with the surface. Also, the propellant particles are traveling in their associated hot gaseous atmosphere when impinging on the surface. Thirdly, the time cycles involved are in milliseconds and the particle velocities (although unknown) are undoubtedly far greater than any of those cited in the literature. Early attempts to measure the velocity of propellant particles in the erosion gage by high speed photography techniques were unsuccessful.

In spite of these differences pointed out in the Mortar system compared to the particle-surface actions cited in the literature, our results will show that the behavior of Mortar steel surfaces and some of the wear characteristics exhibit surprising similarities.

---

6. Olive Engel, "Pits in Metals Caused by Collision With Liquid Drops and Soft Metal Spheres," NBS Journal of Research 62, 229 (1959) RP2958.

7. Olive G. Engel, "Pits in Metals Caused by Collision With Liquid Drops and Rapid Steel Spheres," Journal of Research of the National Bureau of Standards-A Physics and Chemistry Vol. 64A, No. 1, January-February 1960, pp. 61-72.

8. Moore, M.A., Richardson, R.C.D., Attwood, D.G. "The Limiting Strength of Worn Metal Surfaces" Metallurgical Transactions (ASM), Vol 3, Sept 1972, pp. 2485-2491.

FIELD TESTING

Early efforts in searching for a suitable coating to protect the bore of the 81MM Mortar Tube from such erosion consisted of electrodepositing various tube bores with candidate coatings which were then scheduled for field testing using primarily "0" increment rounds (i.e. the most damaging rounds). Since electrodeposited chromium was presently being used as the acceptable erosion resistant coating in high velocity production weapon systems, it was naturally selected as a first choice for test in the Mortar System. Other selected coatings were cobalt-alumina (Al_2O_3) and also a proprietary chromium coating called "Armoloy".

These preliminary efforts to apply wear resistant bore coatings and test firing mortar tubes in the field have been extremely costly and time-consuming because of the large number of rounds required and difficulties encountered with field firing schedules. In view of the latter it was decided to devise a laboratory method of testing so that a variety of coatings could be evaluated concurrently prior to field testing.

EXPERIMENTAL DETAILS

Erosion gage - An erosion tester or gage was designed and developed which utilizes the M285 tail fin assembly inside a chamber holding eight test specimens at the same time to correspond to the 8 rows of holes. (See cut away illustration in Figure 6.) The actual details of construction of the erosion gage will be reported under a separate cover and will not be discussed here. The primary change made in the firing action, is that the projectile has been removed from the tail assembly which is secured to remain stationary during the firing cycle.

The erosion rate of the test material can be increased, so that less rounds are required, by moving the specimens closer to the tail fin assembly which reduces the distance of the jet stream. Upon firing the ignitor charge, the mixture of hot gases and associated burning particles are radially discharged upon the specimen surface through the .125" vent holes.

Fin Assembly - The M170 fin assembly (which was used in all of the tests) houses the M285 ignition cartridge containing the M9 propellant which has a charge weight of 108 grains (1 grain = .0648 gram).

Physical Properties of M9 Propellant - The propellant is in the form of platelets measuring .059 in. in diameter and .010 in. thick. The bulk density is 46 lb/cu-ft.

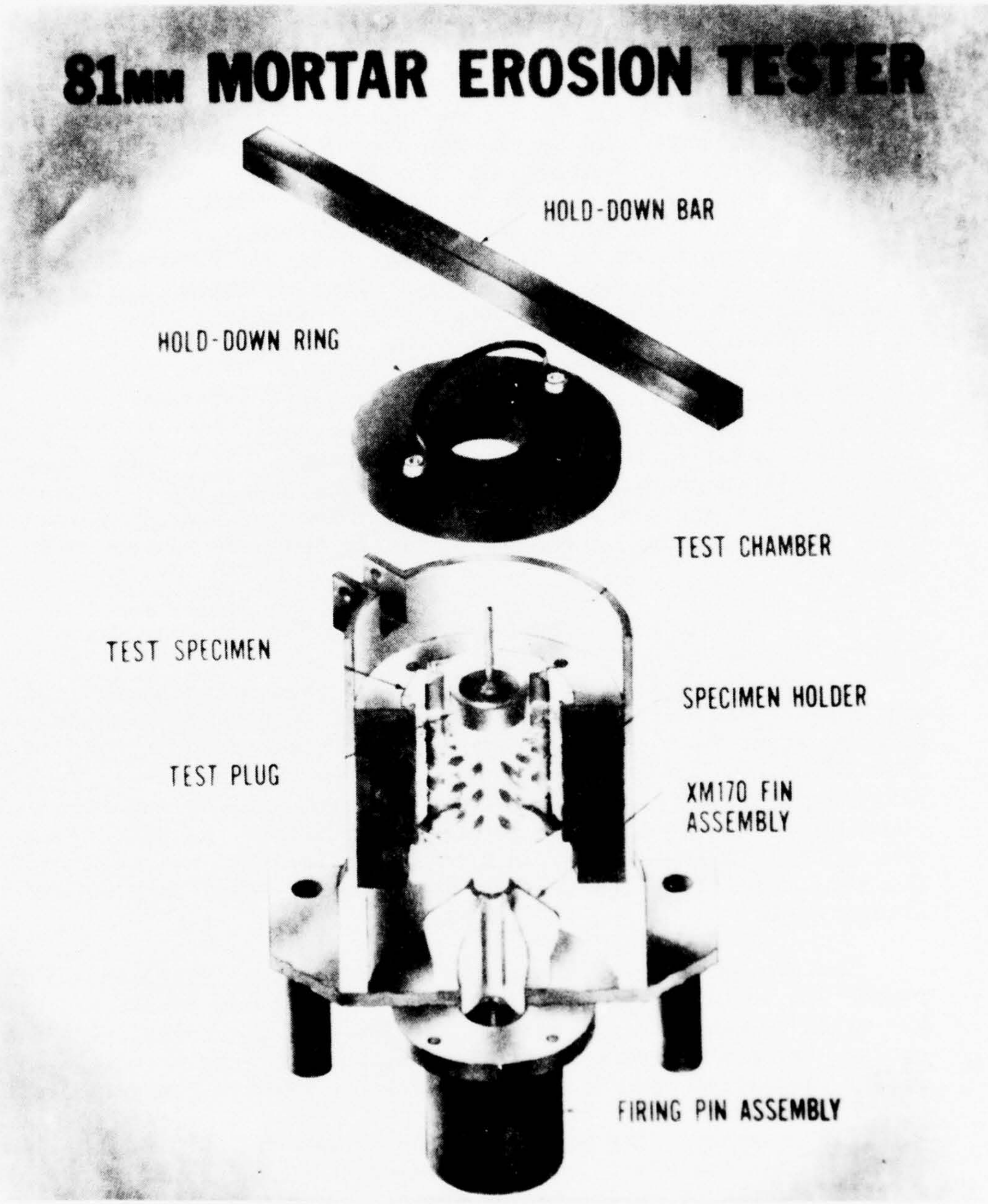


Figure 6. 81mm mortar erosion tester.

Calculated Thermochemical Values for M9 Propellants (as per Spec MIL-P-20306)

Isochoric flame temp, °K	3799
Force, ft-lbs/lb x 10^{-3}	.382
Unoxidized carbon, %	.0
Combustibles, %	32.8
Heat of explosion, cal/gm	1295
Gas volume, moles/gm	.0.03618
Ratio of specific heats	.1.2102
Isobaric flame temp, °K	3139
Covolume, in.^{3}/lb	25.97

Plating Conditions - The bath formulas and plating conditions employed for preparing the surface coatings selected for evaluations are given in Tables 1 and 2, respectively.

TABLE 1. PLATING BATH FORMULATIONS

Bath No	Coating	Bath Formula	Compound Conc. g/l
1	Cobalt (Co)	Cobalt Sulfate ($CoSO_4 \cdot 7H_2O$)	300
		Cobalt Chloride ($CoCl_2 \cdot 6H_2O$)	50.6
		Boric Acid (H_3BO_3)	31.4
2	Cobalt Alumina ($Co-Al_2O_3$)	Cobalt Sulfate	314
		Boric Acid	31.4
		Cobalt Chloride	50.6
		Aluminum (Al_2O_3) (.05u particle size)	25
3	Cobalt-Iron (Co-Fe)	Cobalt Sulfate	314
		Boric Acid	31.4
		Cobalt Chloride	50.6
		Ferrous Sulfate ($FeSO_4 \cdot 7H_2O$)	25
4	Chromium (Cr)	Chromic Anhydride (CrO_3)	250 g/l
		Sulfuric Acid (H_2SO_4)	2.5 g/l
5	Armoloy Cr	*Armoloy Salts	454 g/l

*Supplied by Armoloy Inc., Fort Worth, Texas

TABLE 2. PLATING CONDITIONS

Bath	Current Density	pH	βe'	Bath Temp
Cobalt	5.4 amp/dm^2 (50 amp/ft^2)	2.0	30	60°C (140°F)
Cobalt-Alumina 50 g/l (.05 micron)	5.4 amp/dm^2 (50 amp/ft^2)	2.0	30	60°C (140°F)
Cobalt-Iron (6 wt %)	5.4 amp/dm^2 (50 amp/ft^2)	3.0	30	60°C (140°F)
Chromium	32 amp/dm^2 (300 amp/ft^2)		21-22	54°C (130°F)
Armoloy Cr	32 amp/dm^2 (300 amp/ft^2)		21-22	54°C (130°F)

Post Heat Treatment - All coatings with the exception of Co-Fe were thermal treated in an atmosphere furnace for hydrogen relief after plating at 450°F (232°C) for 4 hrs to insure against embrittlement The Co-Fe coatings were thermally treated at 675°F (357°C) for 4 hrs for the purpose of attempting to impart some ductility to the relatively brittle coatings in the as plated condition.

Nitride Surfaces - The 76-hour nitriding cycle for the 81mm Mortar specimens consisted of treatment at 975°F for 15 hours at 24-28% dissociation and 1020°F for 61 hours at 80-84% dissociation.

Coating Thickness and Wear Measurements - The deposit thickness of iron group metals for this test were 6-8 mils. In the case of chromium deposits, two thicknesses were tested, which were 0.2 mils and 2.0 mils. The thickness of deposits were measured with micrometers and in some cases later verified by measurements of the coatings using the microscopic camera. Wear measurements of all specimens were taken every 125 rds and conducted with a ball micrometer and coordinate measuring instrument (Sheffield Cordex 300 Coordinate Measuring Machine) which had a 1/8" ball tip. The procedure was to slide the test specimen back and forth across the worn depression of the surface until the tip

reached the lowest point which measured the greatest point of wear due to firing.

Weight Measurements - Weight loss determinations, due to erosion during firing, were conducted on a Mettler analytical balance.

Microhardness Measurements - These measurements were made on cross sections of the specimens with a Wilson Tukon microhardness tester using a 100g load and are reported on the Knoop scale. Measurements on the soft steels were taken with a 25g load. Hardness measurements given are those taken before firing unless otherwise stated.

Photomicrographs - Cross sections of specimens were mounted and polished using diamond abrasives. The polished specimens were etched with a solution of 60 parts lactic acid, 30 parts HNO_3 + 5 parts HF, by swabbing for 10-15 seconds. The photomicrographs were made with a Polaroid camera using a Leitz MM5 Research Metallograph.

Test Specimens - The specimens consisted of SAE 4340 steel strips (1/8 inch thick) and cut sections of mortar tubes. The specimens measured 3/4 of an inch wide and five inches in length.

Laboratory Firing Tests - The firing tests were limited to 1500 rds which produced over 10 mils of wear on the radius of unprotected mortar steel. Mortar tubes in the field are condemned when any portion of the bore shows a wear of 20 mils on the diameter (i.e., 10 mils on the side). However, the 1500 rd test was selected to permit a suitable range of wear values for evaluating the various candidate erosion resistant coatings. Since the erosion tester held eight specimens during a firing test, one of the specimens was always unplated mortar steel which acted as the control specimen.

RESULTS AND DISCUSSION

In reviewing the literature, one will find that considerable doubt and controversy exists on the validity of data from erosion vent studies when comparing results with actual field behavior of eroded surfaces and it is agreed that some of the doubts have considerable merit. However. as previously mentioned, in this present laboratory study our erosion gage consists of the actual field system (which includes the M170 Tail Fin Assembly with the M285 Ignitor) with the absence of the mortar projectile. In spite of two primary changes made in the use of the erosion gage for the purpose of accelerating the erosion process, microscopic examination shows a close similarity in the erosion characteristics produced by the two systems. One of these changes included a decrease in the jet distance from the vent holes to the specimen surface which increases the velocity at point of impact. The second change effectively focuses the surface damage on the same circular location rather than dispersing the surface damage when the rounds are circumferentially loaded at random which results in the formation of annular grooves which have been shown previously.

The data compiled from firing tests using the previously described erosion tester is presented as follows:

A. Chamber Pressure

Since the test specimens were placed closer to the tail fin assembly and no serious attempt was made to match the chamber volume of the erosion tester with that of the field Mortar System it was desirable to measure the peak chamber pressure in the tester to determine how close it was to the field system. This pressure was measured at a point away from the jet blast in order to compare the pressure value with that measured in the actual mortar. Suprisingly, the peak pressure value was approximately the same as the 900 psi measured in the field weapon for a "0" increment charge.

B. Measure of Erosion (Wt Loss vs Dimensional Change)

While weight loss of a given specimen may be considered a more exact method of determining the extent of erosion in most cases, it has turned out to be completely unsatisfactory in our present study. Weight loss measurements were found to be inadequate because the surface damage not only included material loss but surface displacement. This surface displacement or distortion is associated with the cold working which was encountered. This continual distortion from additional firing, eventually became part of the material loss as fracturing occurred.

Thickness change was a more accurate method of measuring wear. On a macroscopic scale, the regression of surface pits eventually leads to a profile which is somewhat dished with new pits reforming as firing continues. The deepest point that the 1/8" dia. ball tip (of the coordinate measuring instrument) rested at, represented the most meaningful wear value. Figure 7 shows the ball tip bridging across the series of pits which range in size from approximately 1-5 mils in depth.

C. Comparison of Field Mortar with Erosion Gage

The erosion of a mortar section which has been fired approximately 7500 field rds using "0" increment charges has been compared with that of an average mortar steel test piece fired 1500 rds in the erosion gage. The results are shown in Table 3, whereby the field data on the left side of the table is compared with lab data on the right. The results show that the erosion gage increased the erosion rate on mortar steel by a factor of approximately 4.6 to 1 simply by decreasing the jet distance by 4/10 inches and loading the rounds in a fixed circumferential position so that the gas jets line up on the same spot of each specimen. However, if we compare the distance of the top and bottom jets of either system, the difference is only .140 in. (rather

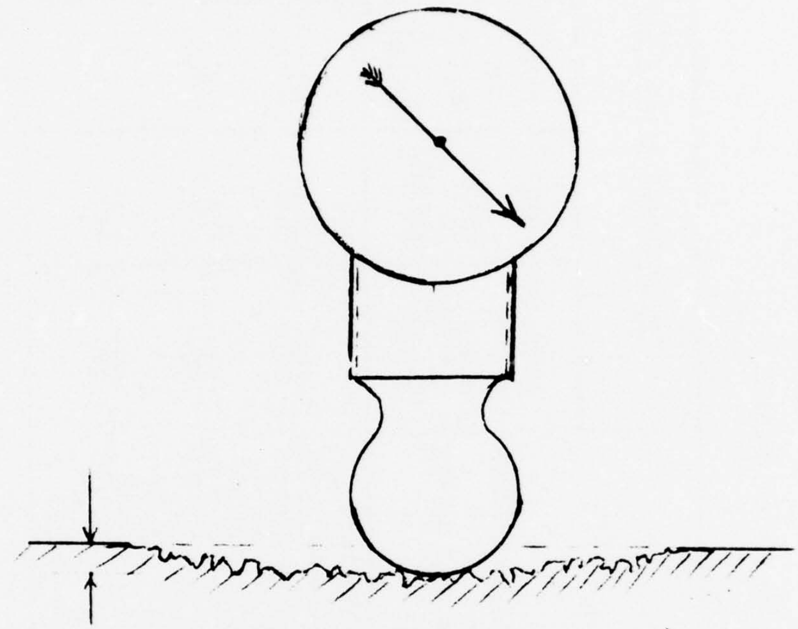
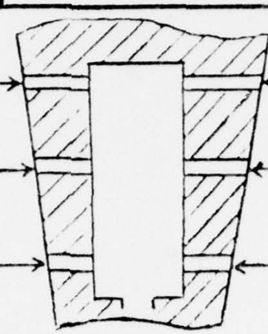
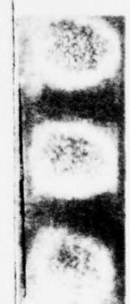


Figure 7. Surface wear measurement - maximum depth determined by a 1/8 inch diameter ball tip.

TABLE 3. COMPARISON OF GAS JET DISTANCE - WEAR RELATION FOR FIELD MORTAR VS LAB EROSION GAGE TESTING ON MORTAR STEELS

FIELD MORTAR SYSTEM AFTER 7500 RDS				M170 TAIL FIN	EROSION GAGE AFTER 1500 RDS			
SURFACE VIEW OF EROSION	WEAR ON RADIUS (MILS)	WEAR PER RD $x10^{-6}in$	DIST. OF JET TO BORE SURFACE (IN.)	(IGNITION CHAMBER WITH .125 IN. DIAM VENT HOLES)	DIST. OF JET TO BORE SURFACE (IN.)	WEAR PER RD $x10^{-6}in$	WEAR ON RADIUS (MILS)	SURFACE VIEW OF EROSION
	14	1.87	.850		.450	8.07	12.1	
	9	1.20	.920		.520	5.8	8.7	
	3	0.40	.990		.590	1.8	2.7	

than 0.40 in.) and the erosion rate is still a factor of about 4.5 to 1. In view of this observation, it was decided to combine the data and plot wear rate vs jet distance which is shown in Figure 8. The bottom or rear vent distance of the erosion gage is 0.260 in. closer than the top vent of the field mortar system in addition to the fixed circumferential loading of the rounds - but still the wear rate is the same for the two systems. This indicates that length of bore travel through the vent hole may be more effective than the jet distance in increasing the impact velocity and subsequent erosion rate. However, the longer bore length is still considered relatively short to significantly increase the particle velocity. Another strong possibility is that more solid particles pass through the forward vents compared to the rear vents due to incomplete ignition which is discussed below. Dealing with ignition systems is more complicated than dealing with propellants in chamber systems. However, based on the observation in Figure 8, and the collection of additional data, it appears that some empirical equation can be developed to calculate erosion in the present system.

D. Pit Formation

It was previously stated that erosion of mortars was due to the impingement of hot gases and associated propellant particles. Observations in our laboratory indicated that the mechanical force contribution to the surface damage was due to unburned as well as partially burned propellant particles striking the surface. After certain intervals of firing, some of these unburned propellant discs were found embedded in the pitted surfaces of the specimens. Some other unburned discs were scattered about the surrounding area of the erosion gage set-up. The surface damage due to solid particles is also confirmed by the grain refinement and subsequent microhardness increase observed along the periphery of the pits during metallographic examination (see Figure 9). It is obvious that severe plastic deformation takes place during the impingement of these unburned and partially ignited propellant particles apparently driven through vent holes by the expanding gases of the inner propellant particles which are first ignited in the cartridge housing. Problems with poor distribution of ignition gases and resultant sporatic local pressures encountered in gun systems have been well documented in the literature.

It is strongly suspected (on the basis of the similarity in surface damage) that this behavior of unburned propellant particles impinging on the surface also occurs in field mortars with "O" increment charges.

E. Relationship of Hardness to Erosion or Wear

Since it was found that mechanical forces played a major role in the present wear problem, the effect of hardness of a steel surface vs erosion was examined. Figure 10 shows the behavior of three types of steels tested on the erosion gage in which hardness is shown to be a significant factor with nitrided surfaces providing the best wear resistance.

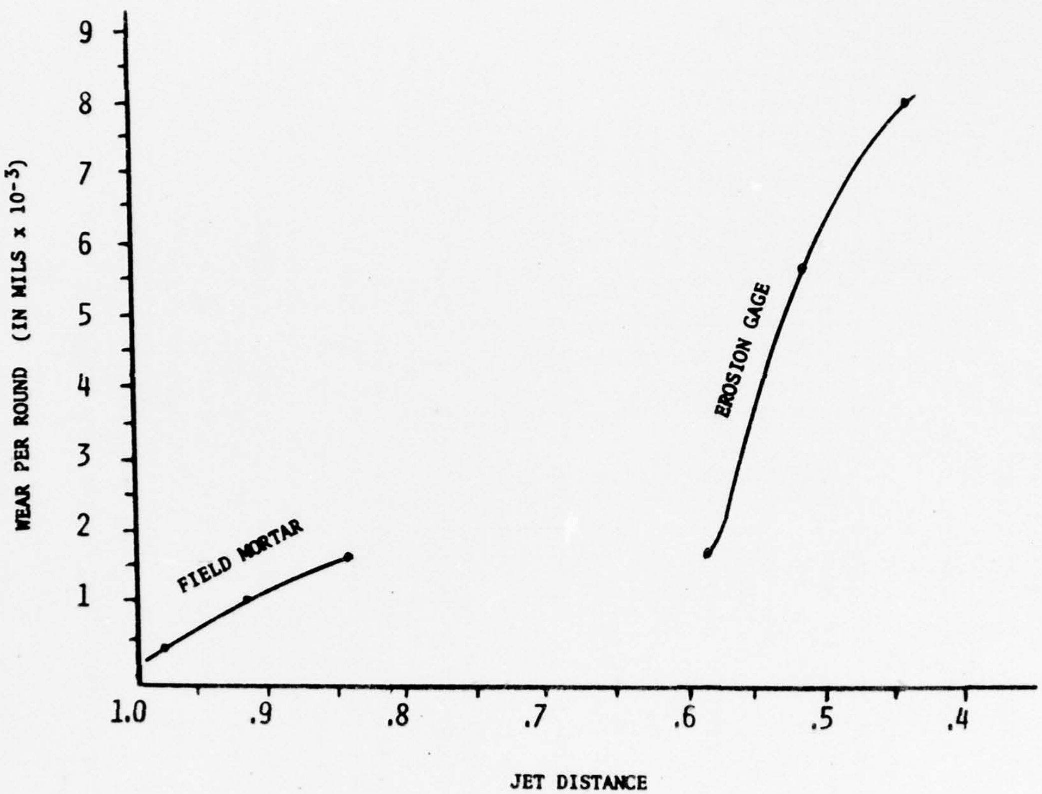


Figure 8. Wear rate vs jet distance for mortar steel (Combining field and erosion gage data).

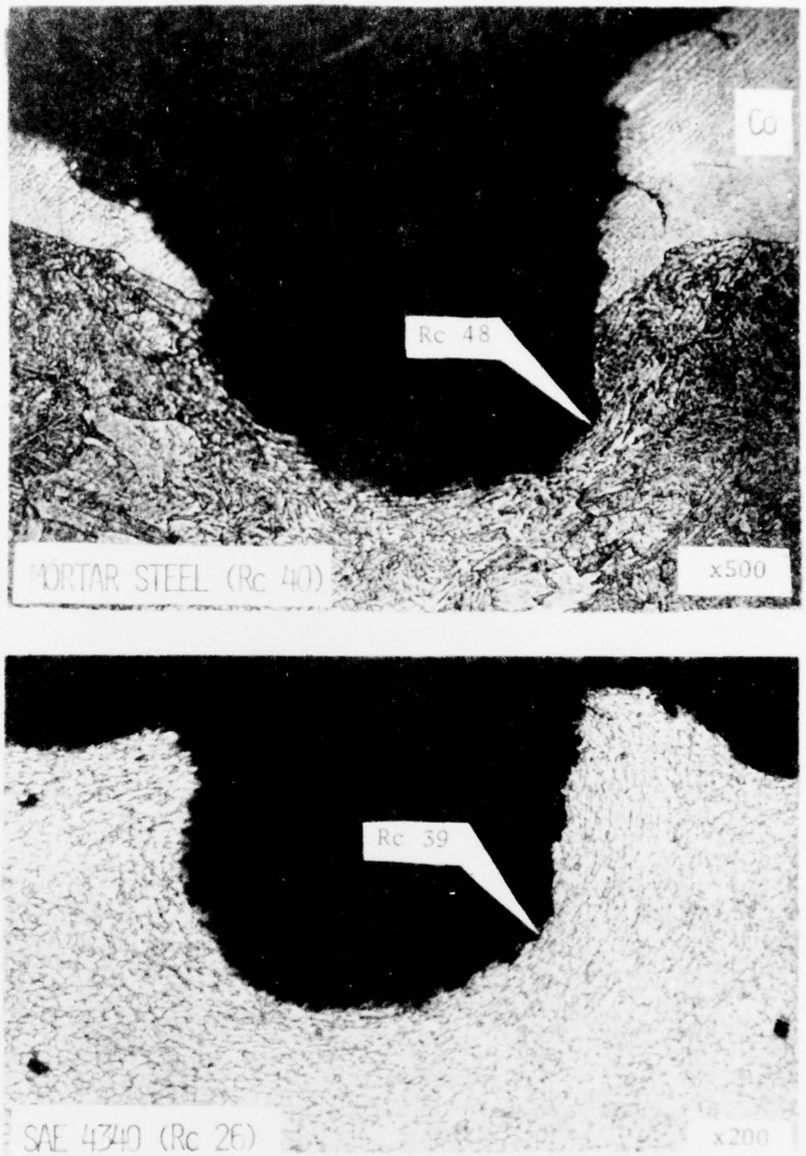


Figure 9. Microscopic cross-sectional view of a pit in two steels (Note fine grain structure along the periphery of the pit due to cold working).

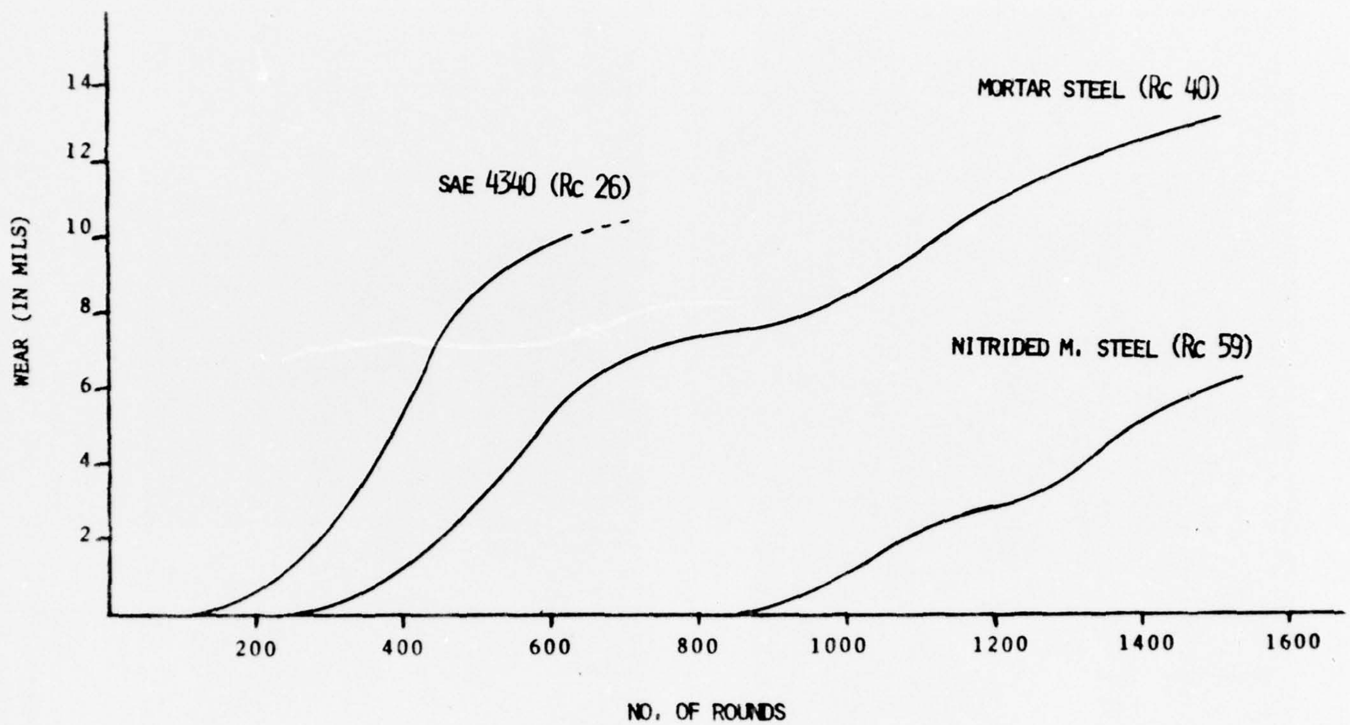


Figure 10. Wear vs round curves showing relation of steel hardness.

The effectiveness of hardness is apparently also demonstrated by the "S" shape of the curves which shows the wear rate to decrease for a period and then increase again. This is attributed to the cold working of the surface which occurs as the degree of pitting becomes extensive. As firing continues, it is speculated that the distortion and plastic deformation of the surface peaks or crests approach a severity whereby fracturing occurs resulting in a sudden increase in the rate of wear as shown by the curves.

The indication that hardness of a surface effectively increases the erosion resistance would lead us to prematurely conclude that a quick solution to the problem is to nitride the bore surface of mortar tubes. Other considerations and findings, however, have ruled out such a decision. These are as follows:

1. The process of nitriding was found to be expensive and time consuming.

2. Surface cracks initiated at the surface, during firing, which propagated through the substrate (i.e. non-nitrided portion of the steel).

3. At the early stage of firing, the nitrided surface is very resistant to wear; however, as firing continues, the brittle casing quickly spalls and fragments leading to a rapid rate of wear and surface regression.

F. Evaluation of Surface Coatings

In view of the beneficial effects of hardness which had been demonstrated earlier, serious considerations were given to this property in our search for a suitable electrodeposited coating.

The erosive behavior of 8 candidate coatings have been studied in this present investigation. The coatings for this study were selected on the basis of cost, ease of application and resistance against surface damage. The comparative performance of 6 of the most promising coatings evaluated during the 1500 rd test, using the lab erosion gage, is presented in Figure 11. The curves represent the average wear vs rds for all of the specimens tested. A minumum of 3 samples were tested for each average presented (with the exception of the Armoloy and Cr on Co coatings).

1. Chromium - Based on the observation of the hardest surface providing the highest resistance to wear, electrodeposited chromium should have proved to be the leading candidate coating since it was the hardest coating. A review of the curves in Figure 11, however, shows that chromium (0.2 mils thick) showed approximately 25% improvement in protecting steel. Previous tests with chromium deposits

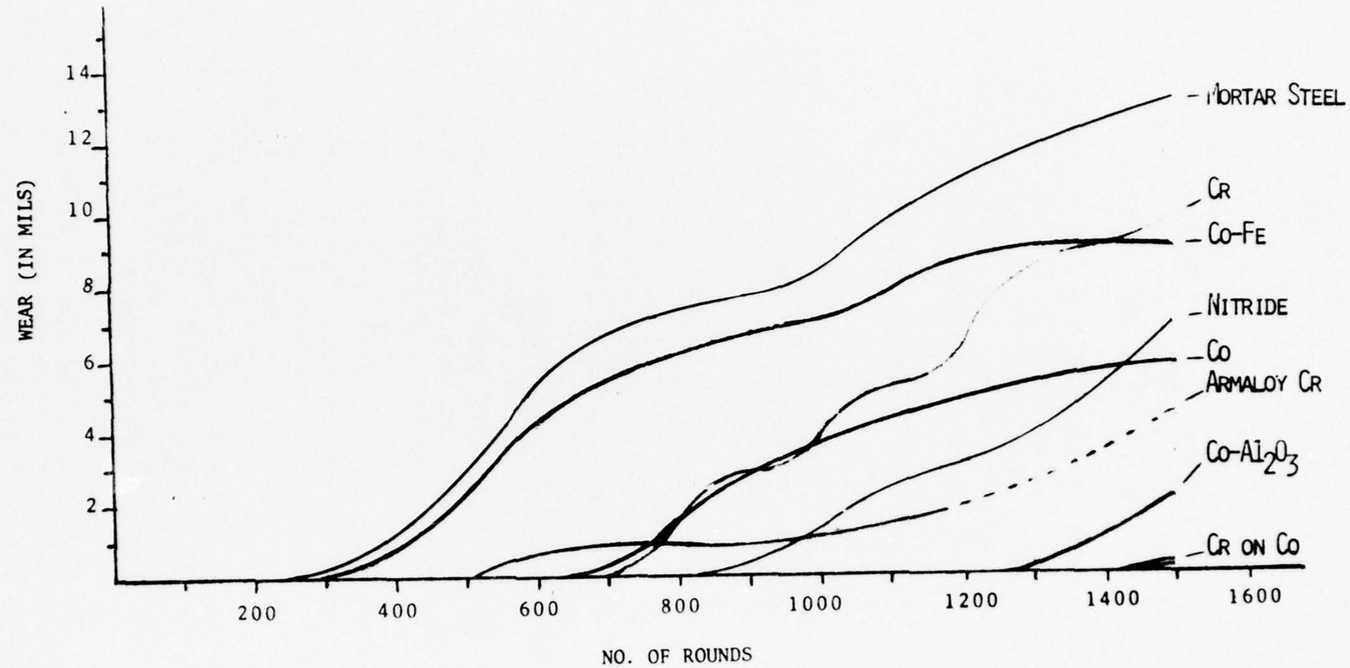


Figure 11. Wear vs round curves comparing various coatings with mortar steel.

which were 2 mils or greater in thickness failed prematurely by excessive spalling and were withdrawn early during the 1500 rd test. Field tests also showed chromium coatings (2-5 mils thick) to perform poorly in a similar manner. An explanation for this behavior can be offered if we look at the wear plot from Finnie et al in Figure 5, which shows a brittle surface to result in greatest wear at a 90° angle of impingement. In reality, electrodeposited chromium can be classified as a brittle surface and therefore explains such a behavior. Figure 12 shows a cross-section of chromium on mortar steel with initial "V" notch segments of chromium progressively sheared away.

Figure 13 shows a surface view of a pitted mortar section. The white patches represent the chromium still remaining.

2. Armoloy Chromium - Coatings of armoloy chromium (which were deposited in a proprietary electrolyte) 1 mil thick were shown to be very promising. However, only one specimen was available for test firing above 1200 rds which is indicated by the dashed line. Other specimens flaked prematurely, and it could not be determined whether the failure was due to the material property or plating defects. In view of the electrolyte being of a proprietary nature and inconsistencies encountered in the deposition process, the study of these deposits was temporarily suspended.

3. Cobalt System of Coatings - We have already discussed the evaluation of nitrided steel, and conventional and armoloy chromium deposits as candidate materials. The remaining materials for discussion are referred to as the cobalt system and can be classified as ductile coatings in contrast to chromium. The wear plots for these coatings are shown separately with mortar steel (which includes their hardness) in Figure 14 in order to simplify the discussion of their evaluation.

In studying the performance of these coatings, it was observed that the erosion resistance generally increased with increasing microhardness but the hardness was not the sole factor in controlling their overall performance. Coatings had to be sound (i.e. free from voids, stress, cracks, and be crystalline), possess high shear and tensile properties and be highly adherent to their substrates in order to be highly resistant to erosion.

a. Co-Fe - The process controls and mechanical properties of Co-Fe alloys have been reported previously from this lab by Sadak and Sautter[9]. In view of some of these properties it was decided to include Co-Fe as one of the candidate coatings. However, a comparison of the wear curves shows cobalt-iron to be the most inferior among the cobalt system. However, this behavior has been attributed to plating problems in which difficulties were encountered in achieving homogeneous and sound deposits of the alloy. Recent improvements in the plating process controls have indicated that Co-Fe (5-12 wt %) should prove to

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9. Sadak, J.C., and Sautter, F.K., J. Vac. Sci. Technol. Vol 11, No. 4 July/Aug 1974 pp. 771-776.

Figure 12. Cross section of chromium deposit on mortar steel with "V" notch sections removed, leading to early failure.

Figure 13. Sectional surface view of pit erosion in 81mm bore after chromium has flaked away (white patches are remaining chromium).

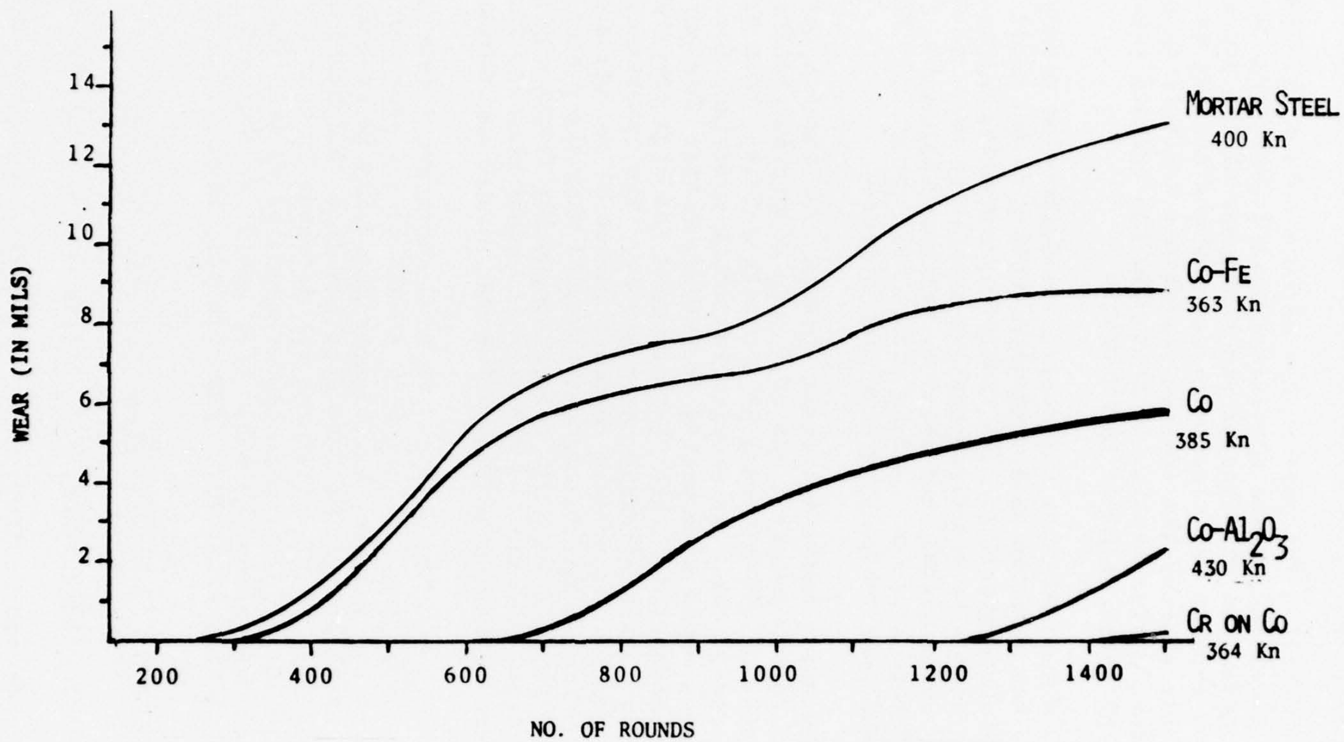

Figure 14. Wear vs round curves comparing cobalt system coatings with mortar steel.

be a strong candidate as an erosion retardant coating in 81mm mortars.

b. Cobalt - The performance of pure cobalt was comparable to nitrided steel and eroded approximately 1/2 the amount as mortar steel. The influence of adhesion and soundness of the deposit on its resistance to erosion was clearly evident by the testing of an earlier group of cobalt whereby the erosion resistance was only approximately 25% better than mortar steel. In this case the surface regressed by the flaking of large chips of the deposit.

c. Cobalt-Alumina - ($Co-Al_2O_3$) - Dispersion strengthened cobalt alloy was selected as a candidate coating on the basis of its high temperature properties. The concept of preparing dispersion strengthened alloys by electrodeposition techniques was first reported by Sautter[10] using nickel, and later by Greco and Baldauf[11]. The properties of electrodeposited $Co-Al_2O_3$ alloys were reported by Sadak and Sautter[12], and more recently by Chen and Sautter[13].

Dispersion hardened cobalt deposits for the present test consisted of approximately 2 v/o of finely dispersed alumina (having a particle size of .05 microns) in a cobalt matrix. This alloy was found to be one of the best erosion resistant materials for this test. $Co-Al_2O_3$ alloys would be expected to perform better than pure cobalt, since their hardness is higher both at room and high temperature and their shear and yield strength are superior. The importance of obtaining sound and homogeneous deposits cannot be overstressed, since a large variation in the erosion rate results when the process controls are not under close observation. Non-homogeneity frequently leads to spalling of large fragments of the deposit rather than the fine microscopic surface regression normally observed in unplated mortars.

d. Chromium on Cobalt - We have shown previously that chromium deposits on steel (2-5 mils thick) showed poor performance in mortars due to its inherent brittleness resulting in progressive spalling of the coating. Thinner deposits (i.e. 0.2 mils) directly on steel offered better protection but the decrease in wear was only approximately 25%. Furthermore cobalt deposits by themselves were classified as fair among the other coatings (i.e. the wear rate was 50% compared to mortar steel). Nevertheless, Figure 14 shows Cr on

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10. Sautter, F.K., J. Electrochem. Soc. 110, 557 1953.

11. Greco, V.P. and Baldauf, W., Plating Journal, pp. 250-257, Mar 1968.

12. Sadak, J.C. and Sautter, F.K., J. Metals Eng. Qtrly, Aug 1974.

13. Chen, E.S., and Sautter, F.K., Plating and Surface Finishing, Sept. 1976.

cobalt to offer the highest resistance against erosion when compared with all other coatings. This infers that by combining the 2 coatings we have capitalized on their erosion resistance beyond their protective quality as individual coatings. This means that some combined effect must exist at the interface of Cr and Co. In addition, the chromium deposit was only 2-5 tenths of a mil thick over 6 mils of cobalt. Thin deposits of Cr are relatively strong compared to thick deposits and do not shear or spall readily. However, thin deposits directly on steel did not perform as well, probably because when the thin Cr flaked away, the underlying steel pitted and the surface regressed at a relatively high rate but thin Cr on cobalt appeared to shear away in a gradual manner with the underlying cobalt still being very resistant to the impinging gases. It must be pointed out that the sampling of Cr on Co is limited and efforts in this area must be continued to explain the combined effect of Cr on Co as an erosion resistant material.

CONCLUSIONS

It should be apparent from the above study that the evaluation and selection of a coating for the protection of mortar bores against annular groove erosion, is incomplete. However, based on the present data which has been evaluated, two coatings warrant further study. These are:

a. $Co\text{-}Al_2O_3$ (5-7 mils thick)

b. Chromium (0.2-0.5 mils) on Cobalt (5 mils)

Continued firing in the erosion gage with these coatings should provide sufficient data to determine the best coatings to be recommended for field testing.

One can conclude from the present data, however, that:

a. The erosion gage has shown to be a useful tool for evaluating erosion resistant coatings for mortar bores.

b. The comparison of the surface damage characteristics produced by the gage and field mortar are very similar.

c. The major cause of pitting erosion in the present system is the impingement of unburned ignitor propellant.

d. The gage accelerates the erosion rate compared to the field system by a factor of approximately 4.5 to 1.

e. The cobalt system of coatings will significantly reduce the annular groove erosion in mortar bores.

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